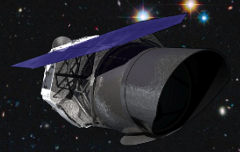
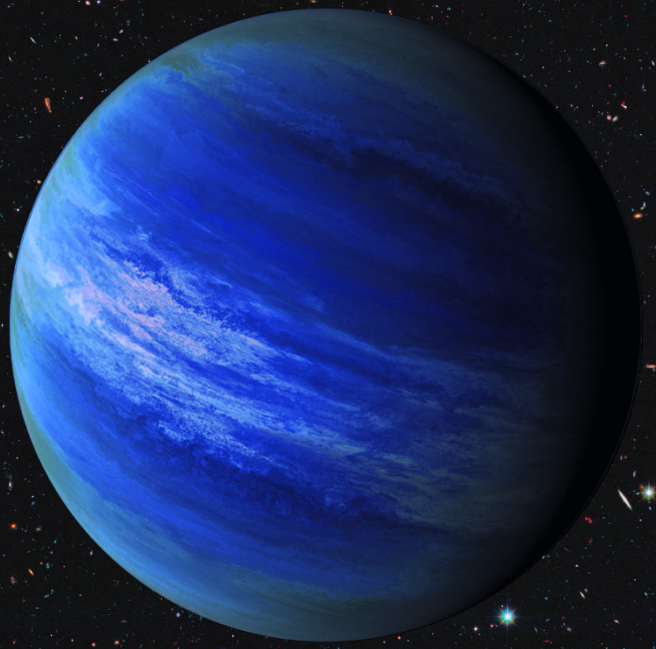


Imaging Exoplanetary Systems with the WFIRST Coronagraph Instrument



Dr. Vanessa Bailey

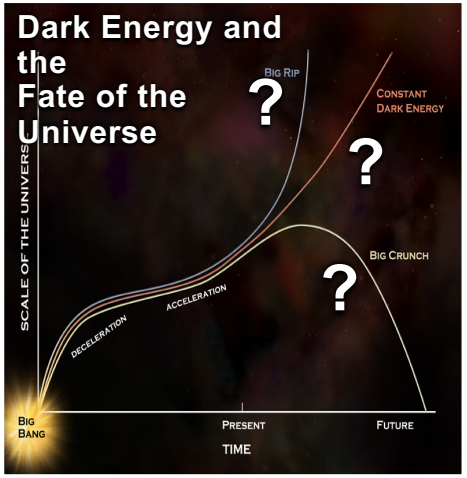
Jet Propulsion Laboratory

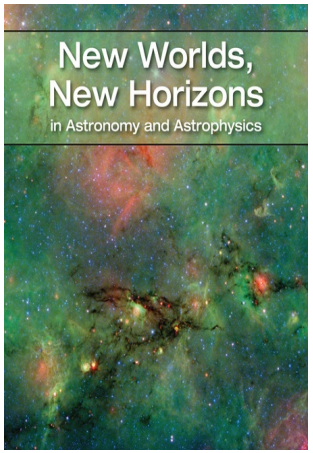
California Institute of Technology

October 18, 2018

Mission Objectives

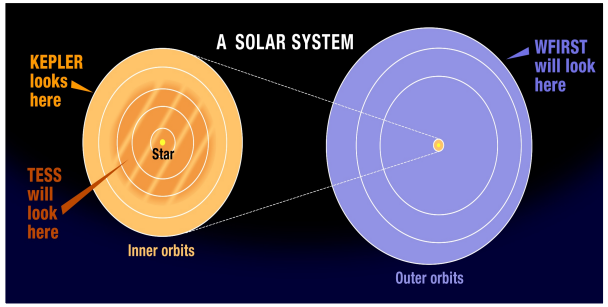
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS



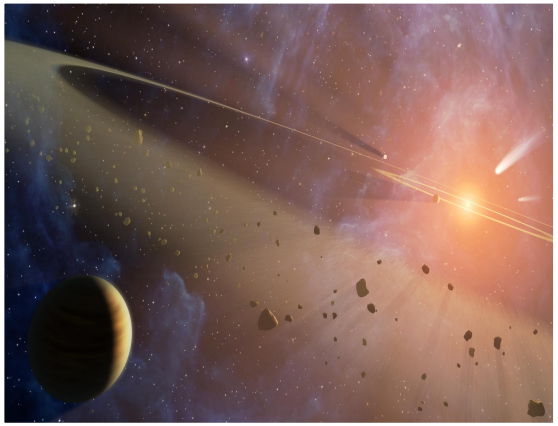


National Academy of Sciences
Astronomy & Astrophysics
Decadal Survey (2010)

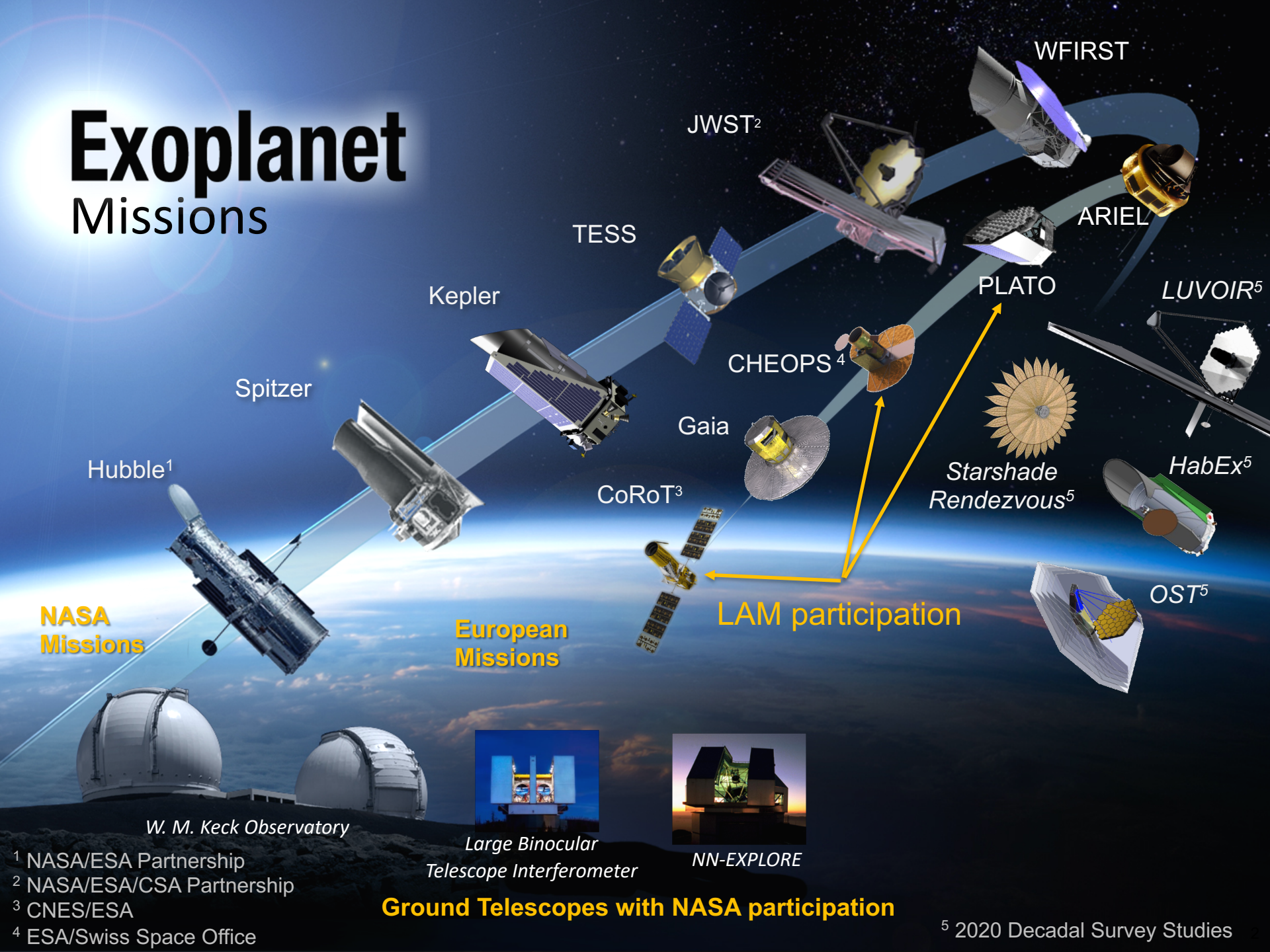
The full distribution of planets around stars



Technology development for Exploration of New Worlds



Exoplanet Missions



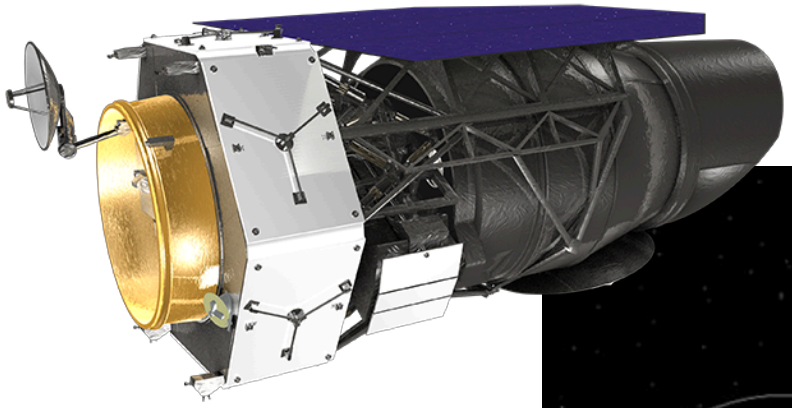
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office

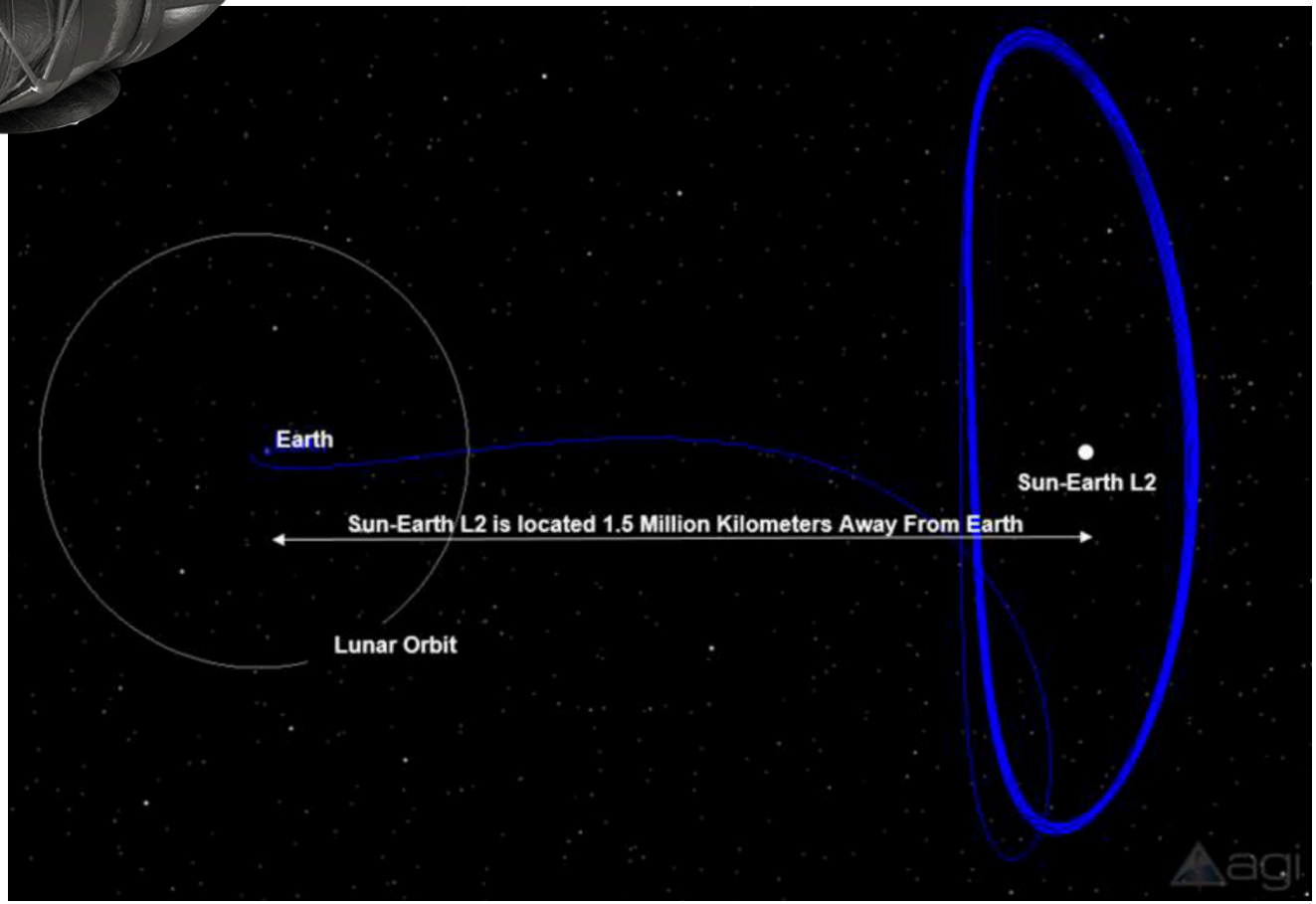
Ground Telescopes with NASA participation

[5] 2020 Decadal Survey Studies

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

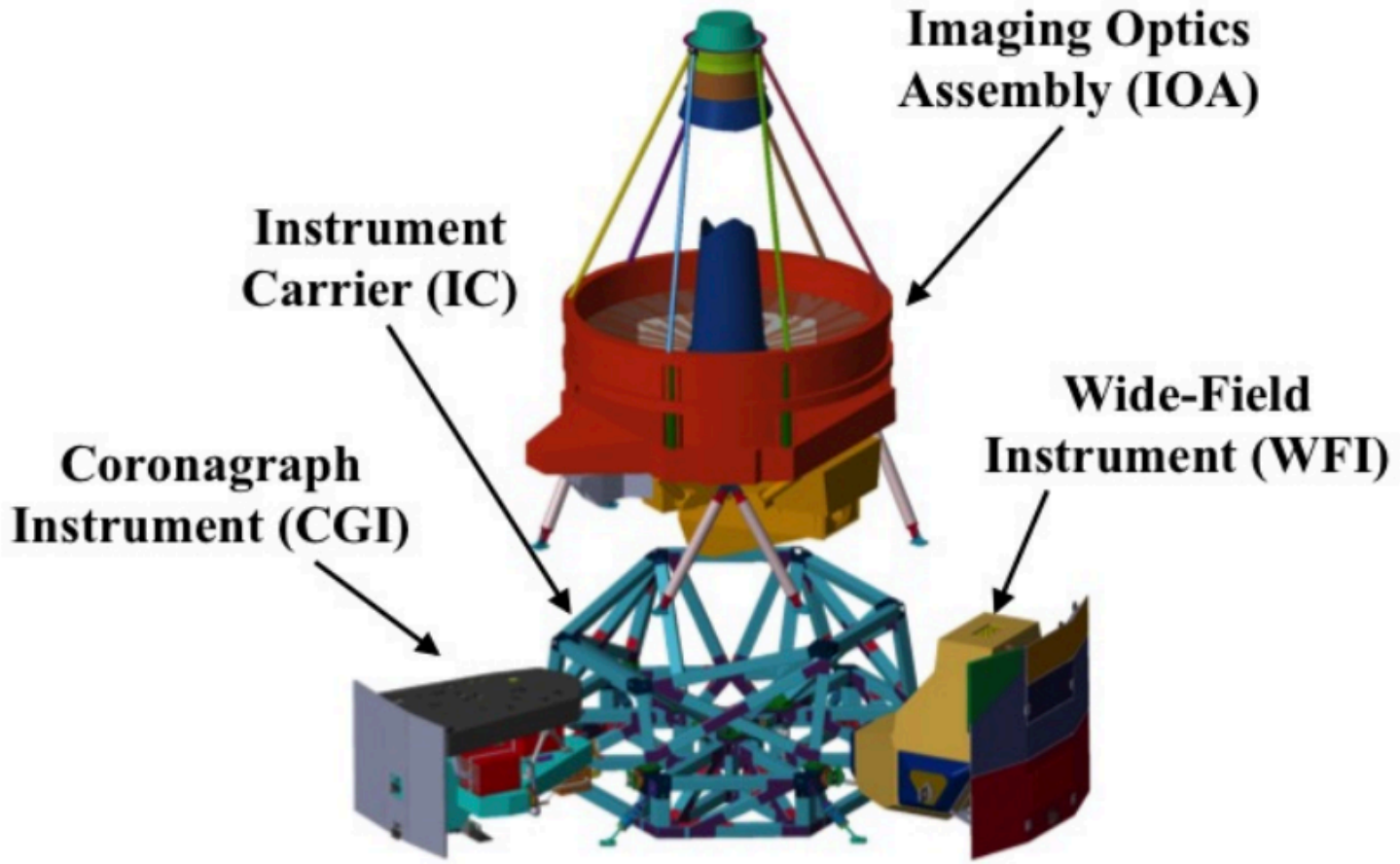
WFIRST will launch late 2025 & orbit at L2





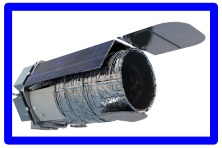
WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

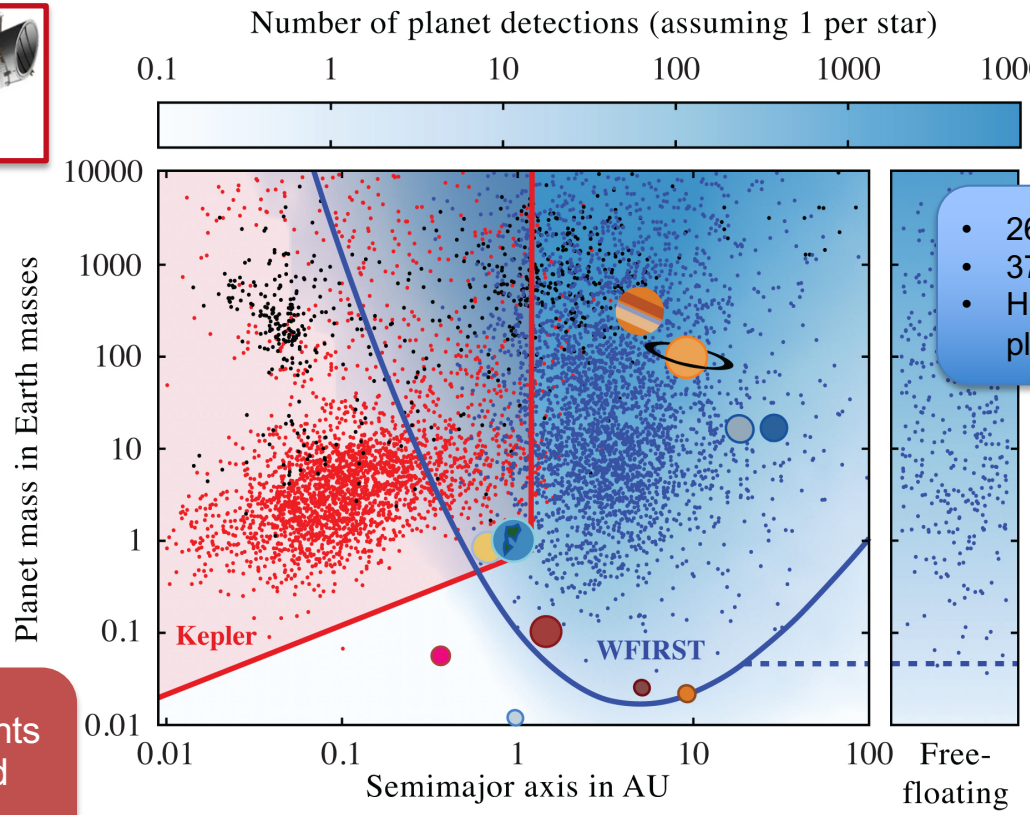
WFIRST has 2 instruments: WFI & CGI



Expanded view of the WFIRST payload

WFI = microlensing





- 2600 planet detections.
- 370 with Earth mass and below.
- Hundreds of free-floating planets.

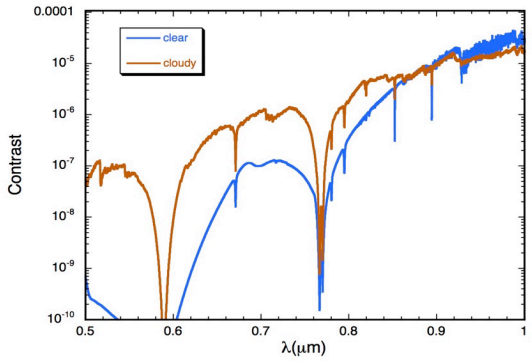
WFIRST complements Kepler, TESS, and PLATO.

M. Penny (OSU)

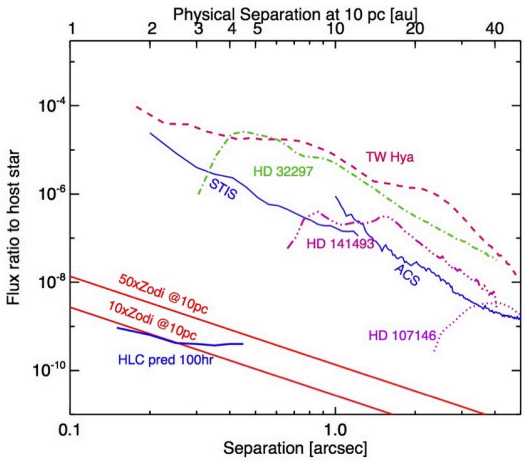
CGI Exoplanetary Science Themes

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

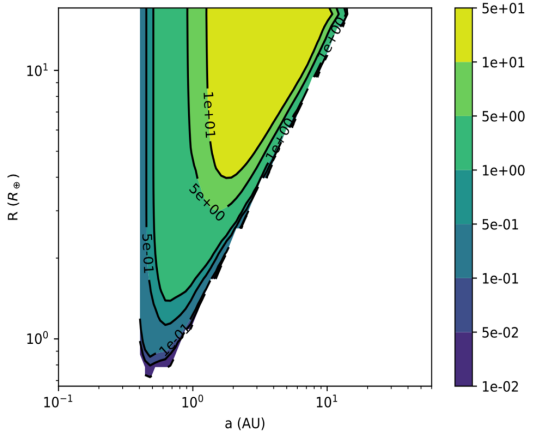
Self-luminous, young super Jupiters: atm. properties



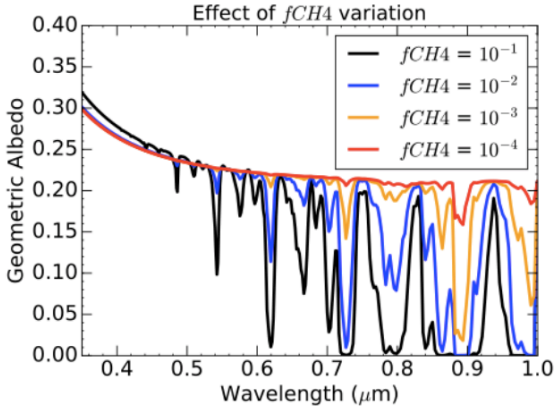
Circumstellar disks:
Protoplanetary (young)
Debris (mature)
Exozodi (mature, HZ)

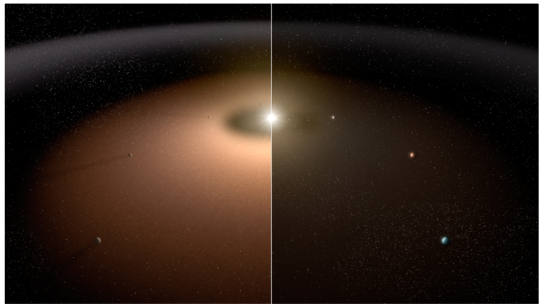


Possible blind searches for giant planets



Mature Jupiter analogues in reflected light: mass & atm. properties





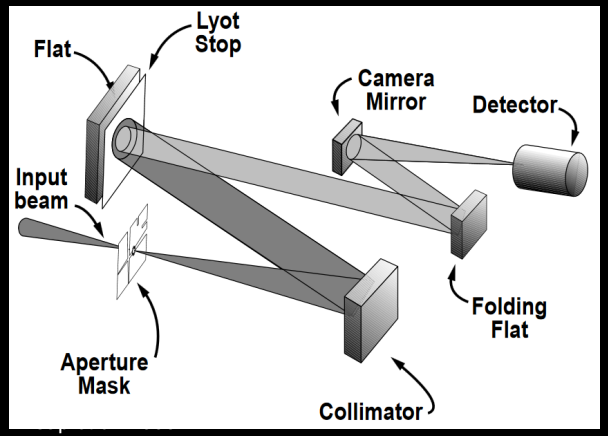
Possible characterization of Habitable Zone of nearby systems

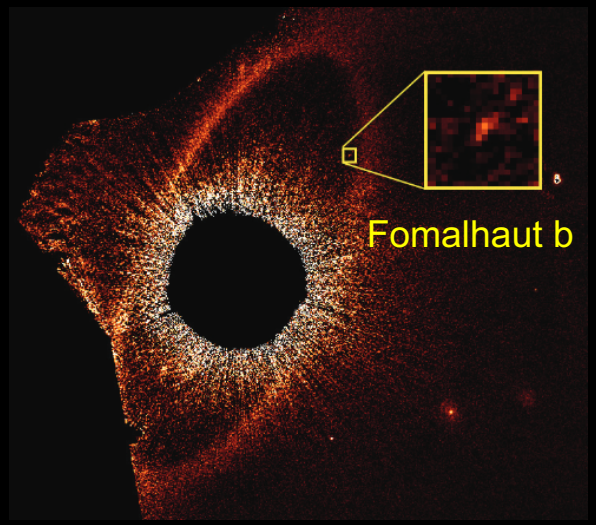
Imaging exoplanets with HST – no active optics

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

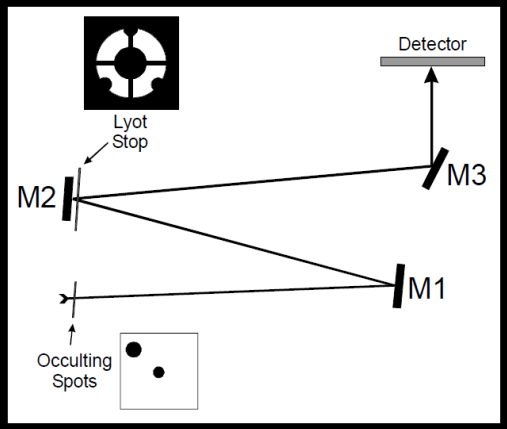
Hubble has had three Lyot coronagraphs used in its instruments to look at planets:

STIS

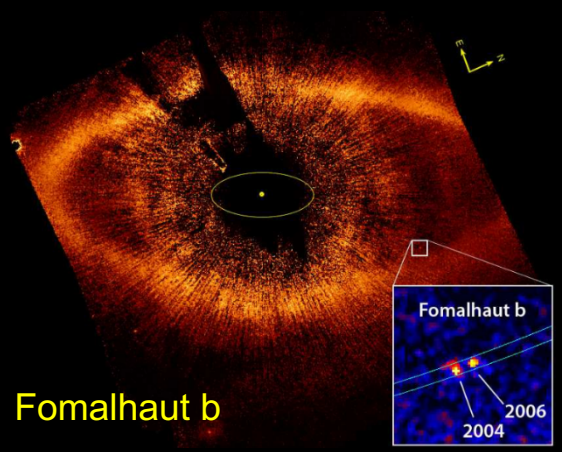




ACS/HRC

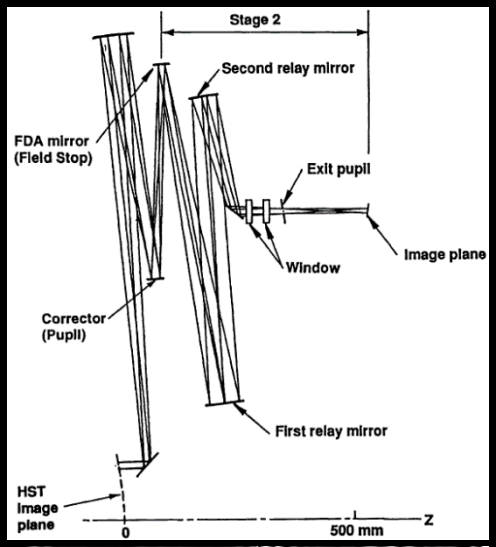


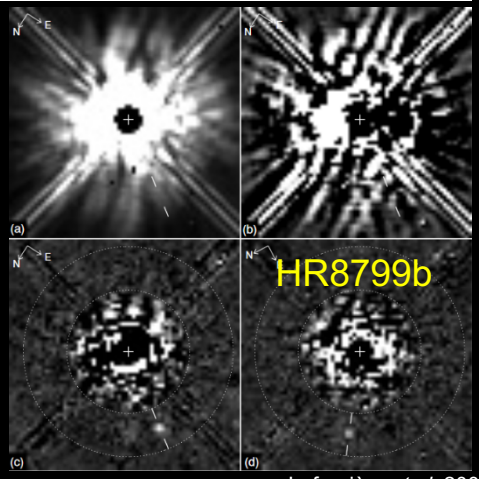
Krist *et al.*2003



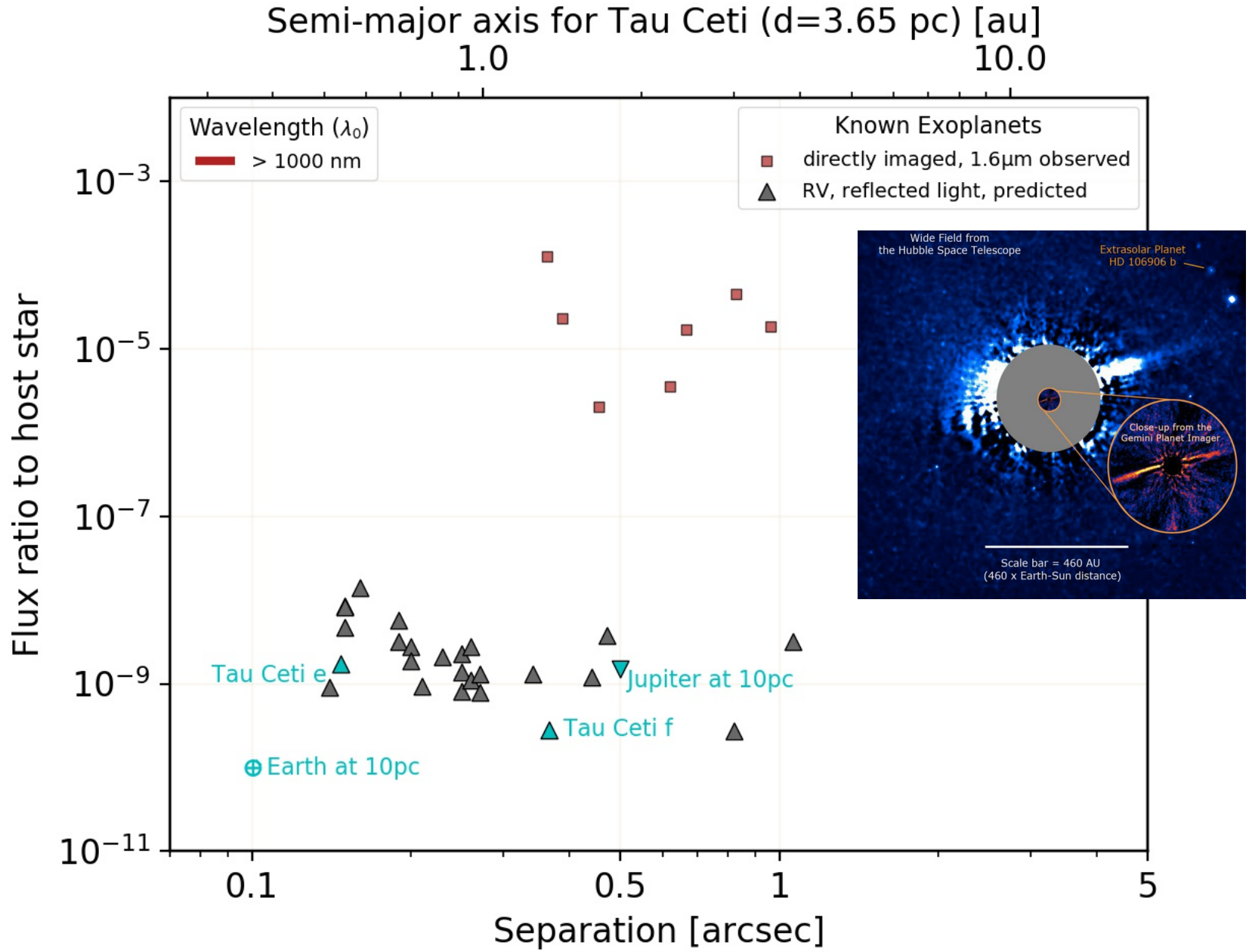
Kalas *et al.* 2008

NICMOS

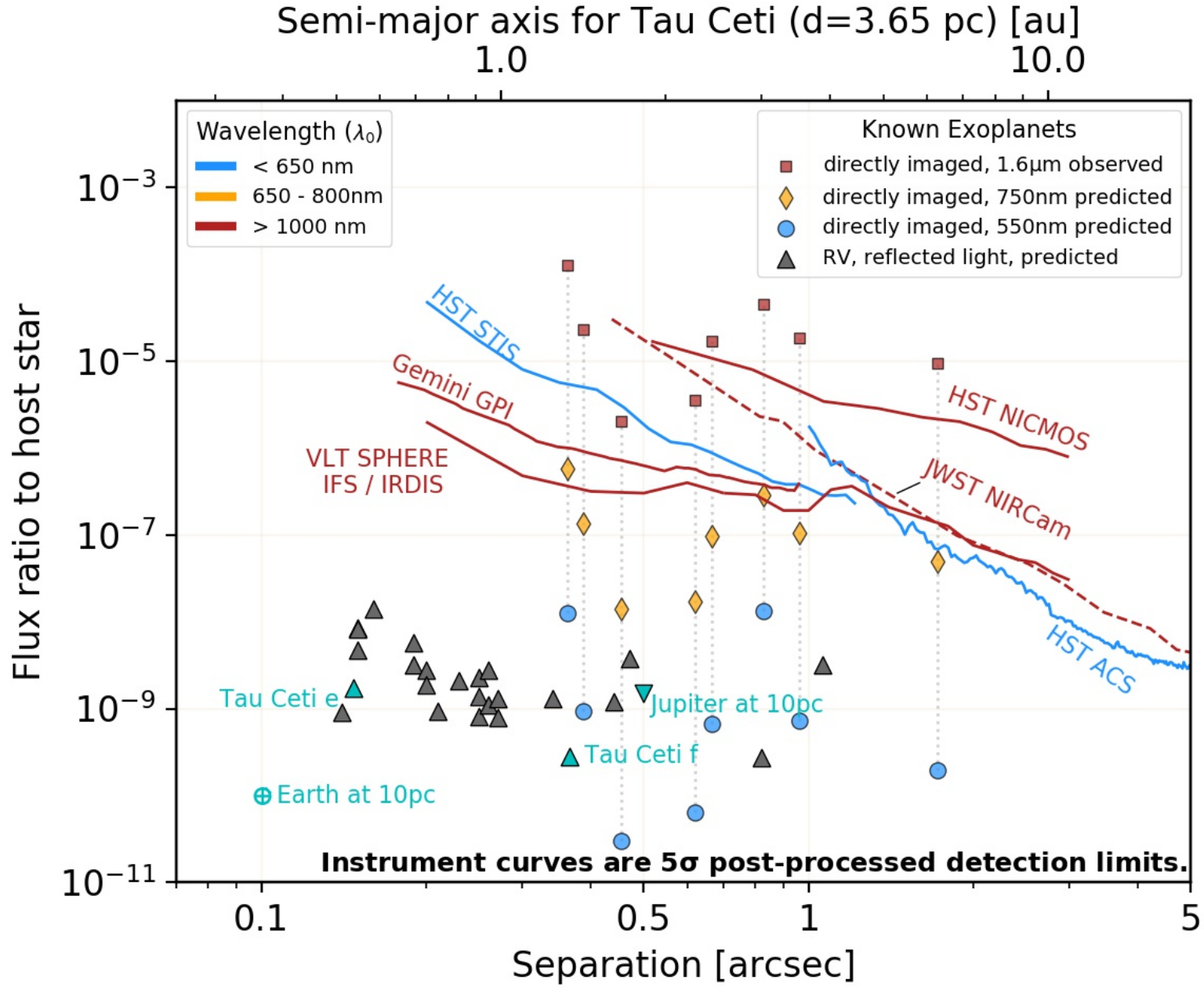




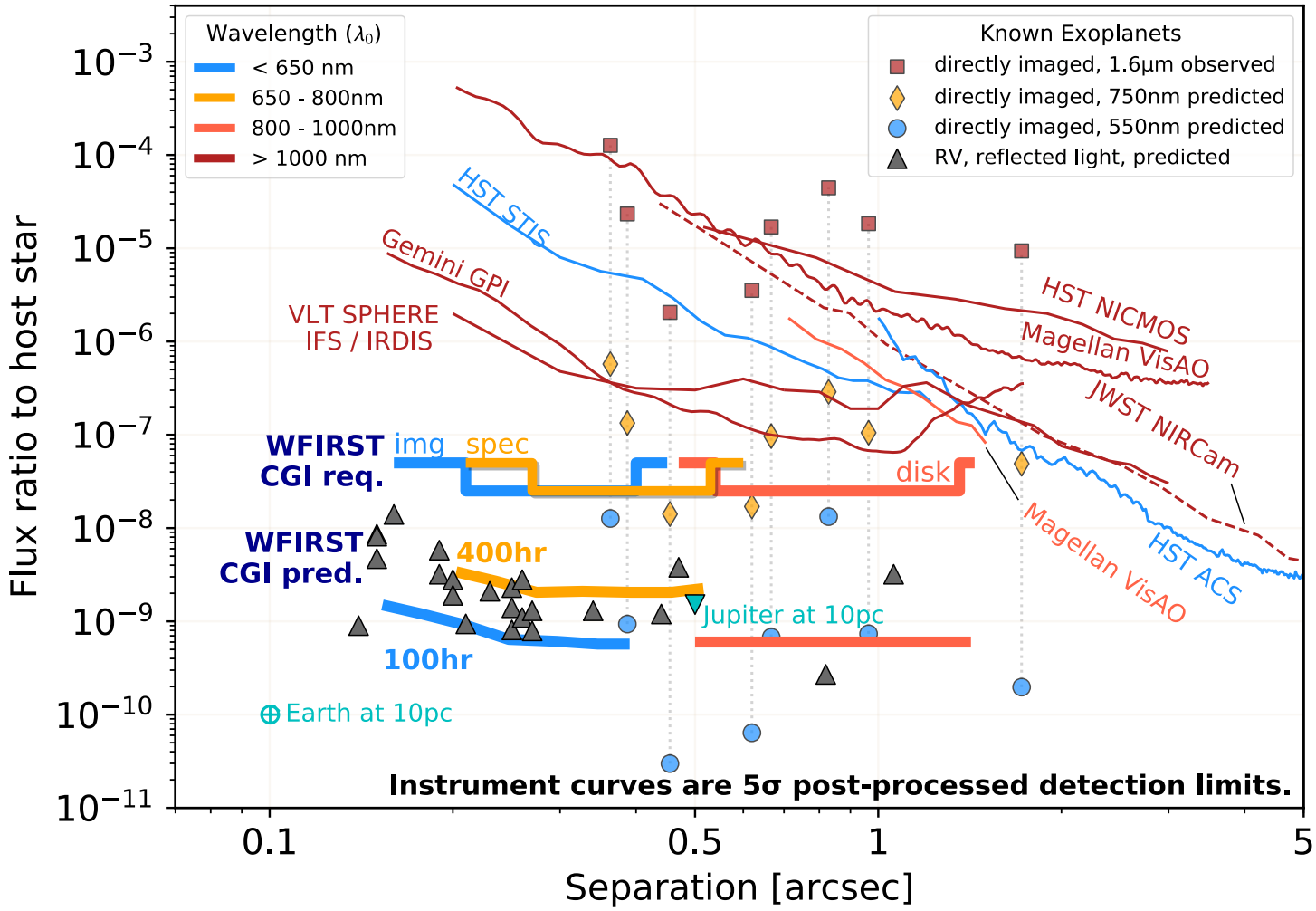
Lafrenière *et al.* 2009



WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

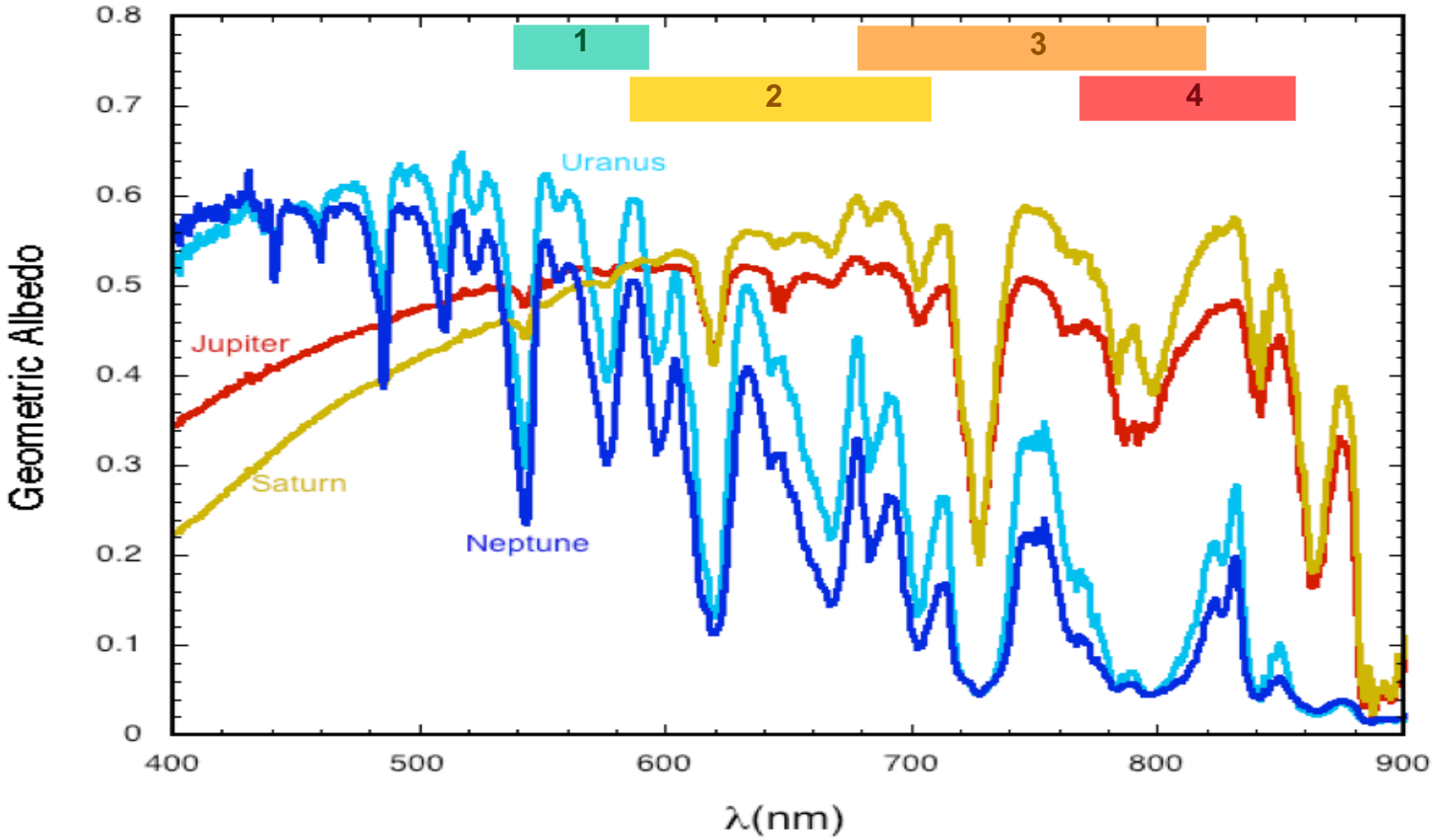

Semi-major axis for Tau Ceti (d=3.65 pc) [au]
1.0
10.0
Wavelength (λ_0)
< 650 nm
650 - 800nm
> 1000 nm
Known Exoplanets
directly imaged, 1.6μm observed
directly imaged, 750nm predicted
directly imaged, 550nm predicted
RV, reflected light, predicted
HST STIS
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
HST ACS
Tau Ceti e
Jupiter at 10pc
Tau Ceti f
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
0.1
0.5
1
5
Separation [arcsec]

Required & Predicted CGI Performance in the Context of Existing Astronomy Capabilities



Baseline Filters

λ_1=575 nm, 10% λ_2=660 nm, 18% λ_3=760 nm, 18% λ_4=825 nm, 10%

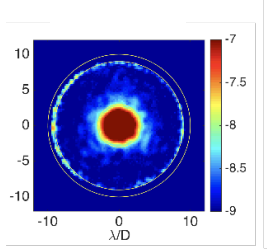


CGI Official Modes

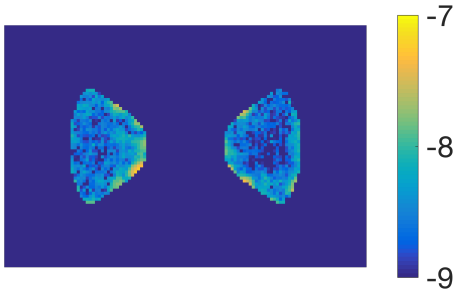
These three "official" modes will be fully commissioned before launch.
ie: the flight hardware will by fully tested with flight software prior to launch.

CGI Filter	λ_{center} (nm)	BW	Channel	Mask Type	Working Angle	Can use w/ linear polarizers	Starlight Suppression Region
1	575	10%	Imager	HLC	3-9 λ/D	Y	360°
3	760	18%	IFS	SPC bowtie	3-9 λ/D		130°
4	825	10%	Imager	SPC wide FOV	6.5-20 λ/D	Y	360°

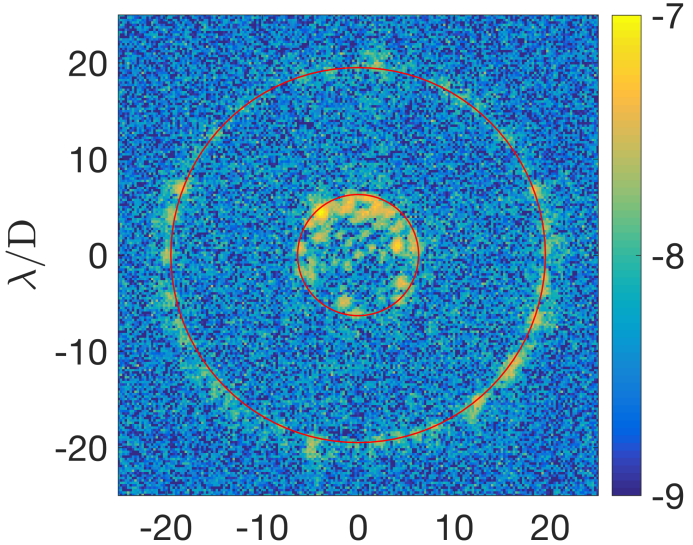
Imaging w/ Narrow FoV
HCIT Lab Image



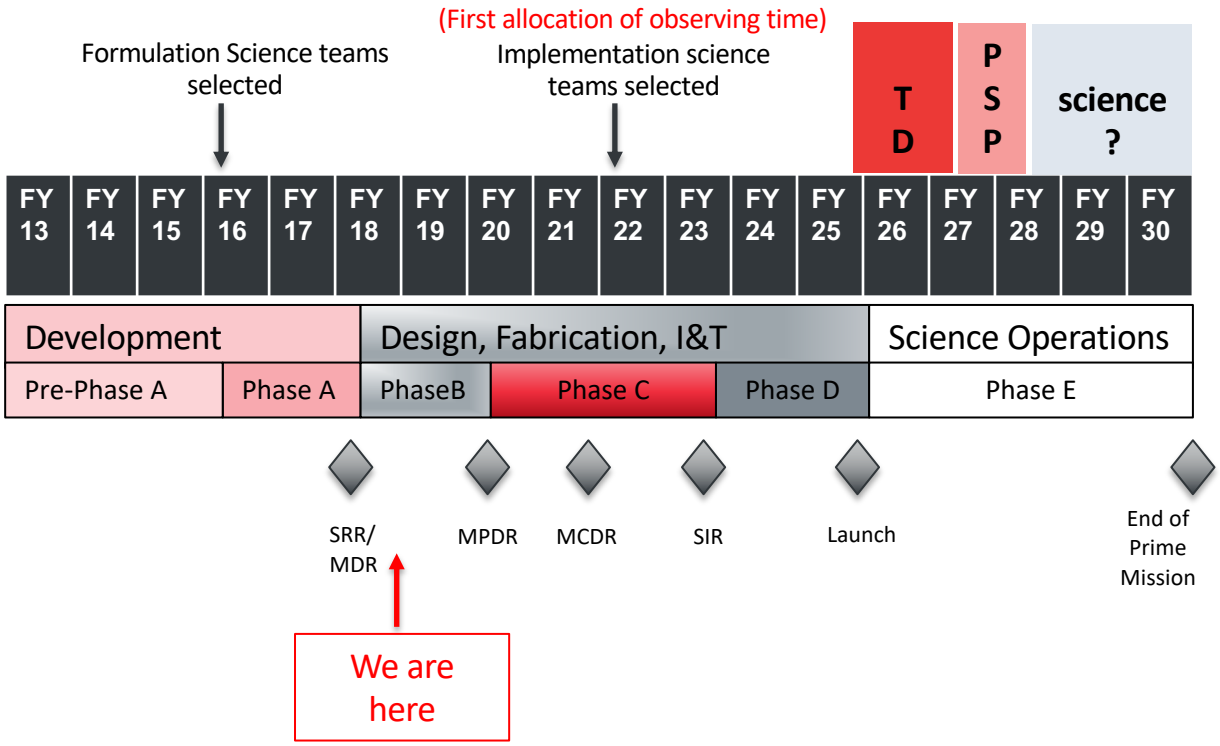
Spectroscopy
HCIT Lab Image



Imaging w/ Wide FoV
HCIT Lab Image



Project Schedule



- **3 months** of *guaranteed* "tech demo" observing in first **1.5 years** of mission
- *If successful*, **1 year Participating Science Program** (**shared** w/ WFI)
- *If successful*, follow-on **2.5 year (shared) science program**
- Potential for extended mission for years 5-10?

National Academy of Science: Exoplanet Science Strategy, Sept 2018

WFIRST Will Provide Critical Exoplanet Data and Pave the Way for a Direct-Imaging Mission

FINDING: A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.

FINDING: A number of activities, including precursor and concurrent observations using ground- and space-based facilities, would optimize the scientific yield of the WFIRST microlensing survey.

FINDING: Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will allow testing of newly developed algorithms and methods.

FINDING: The WFIRST-Coronagraph Instrument (CGI) at current capabilities will carry out important measurements of extrasolar zodiacal dust around nearby stars at greater sensitivity than any other current or near-term facility.

RECOMMENDATION: NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

The National Academies of SCIENCES ENGINEERING MEDICINE

WFIRST WIDE-FIELD INFRARED SURVEY TELESCOPE ASTROPHYSICS • DARK ENERGY • EXOPLANETS

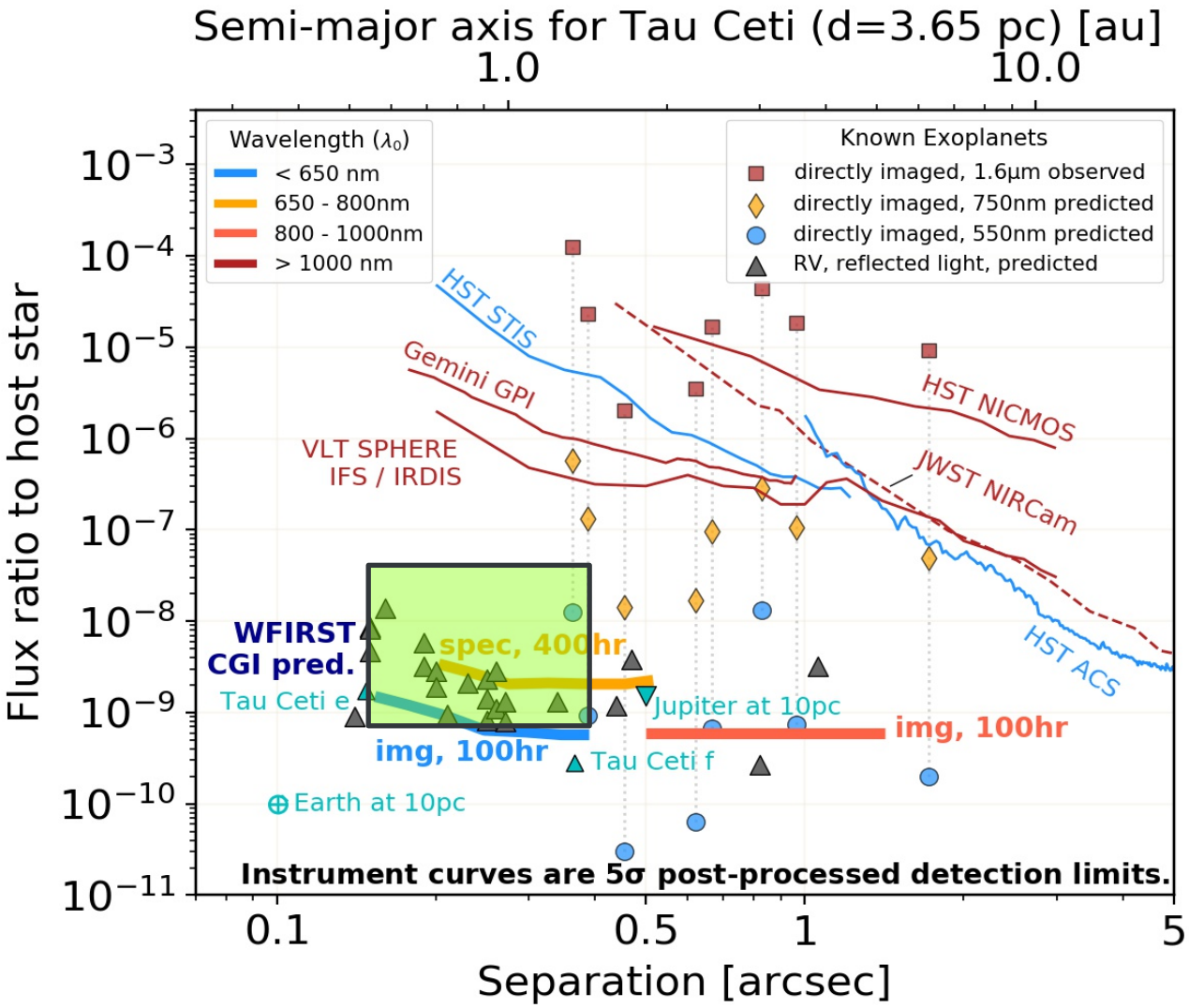
Project Status

- System Requirements Review / Mission Definition Review held February 27 – March 1
  - Do we have the right requirements? / Does the mission design meet those requirements?
- KDP-B completed May 22, 2018
  - **WFIRST now in Phase B!**
  - Integral Field Channel descoped – 4/27/2018 (CSA Budget Constraints)

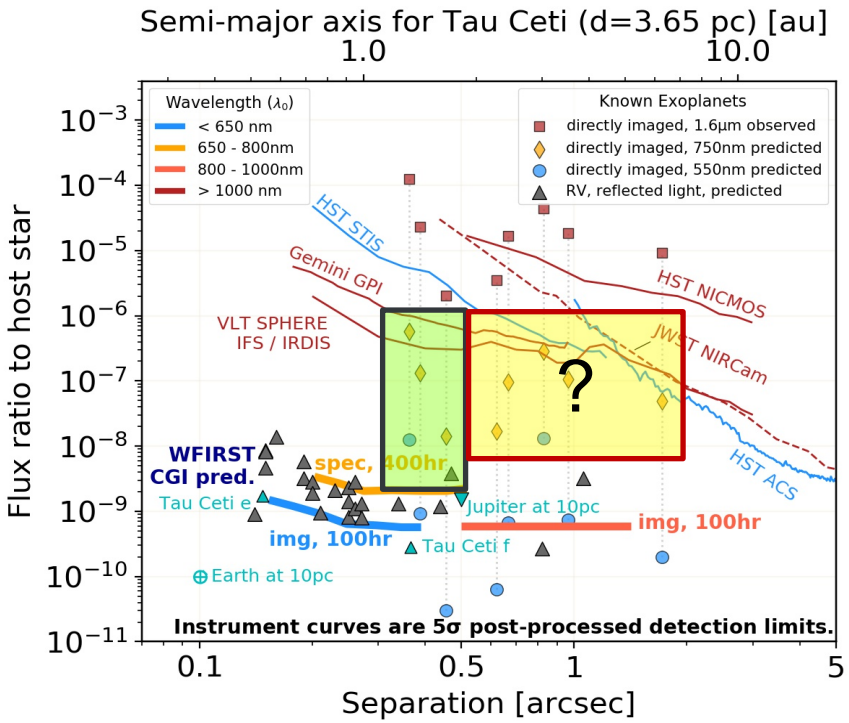
- White House FY2019 budget proposed termination of WFIRST to fund other priorities
- Direction from HQ is to proceed while Congress deliberates
  - *Preliminary indications are that WFIRST will be fully funded in FY2019*

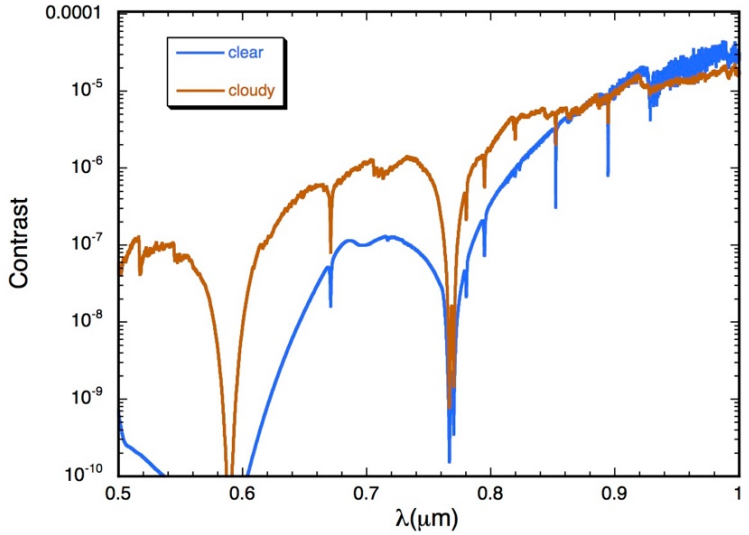
- Notional schedule:
  - PDR: late 2019
  - CDR: mid 2021
  - **Launch: 3rd quarter 2025**

Break vsin(i) mass degeneracy for RV planets with reflected light imaging



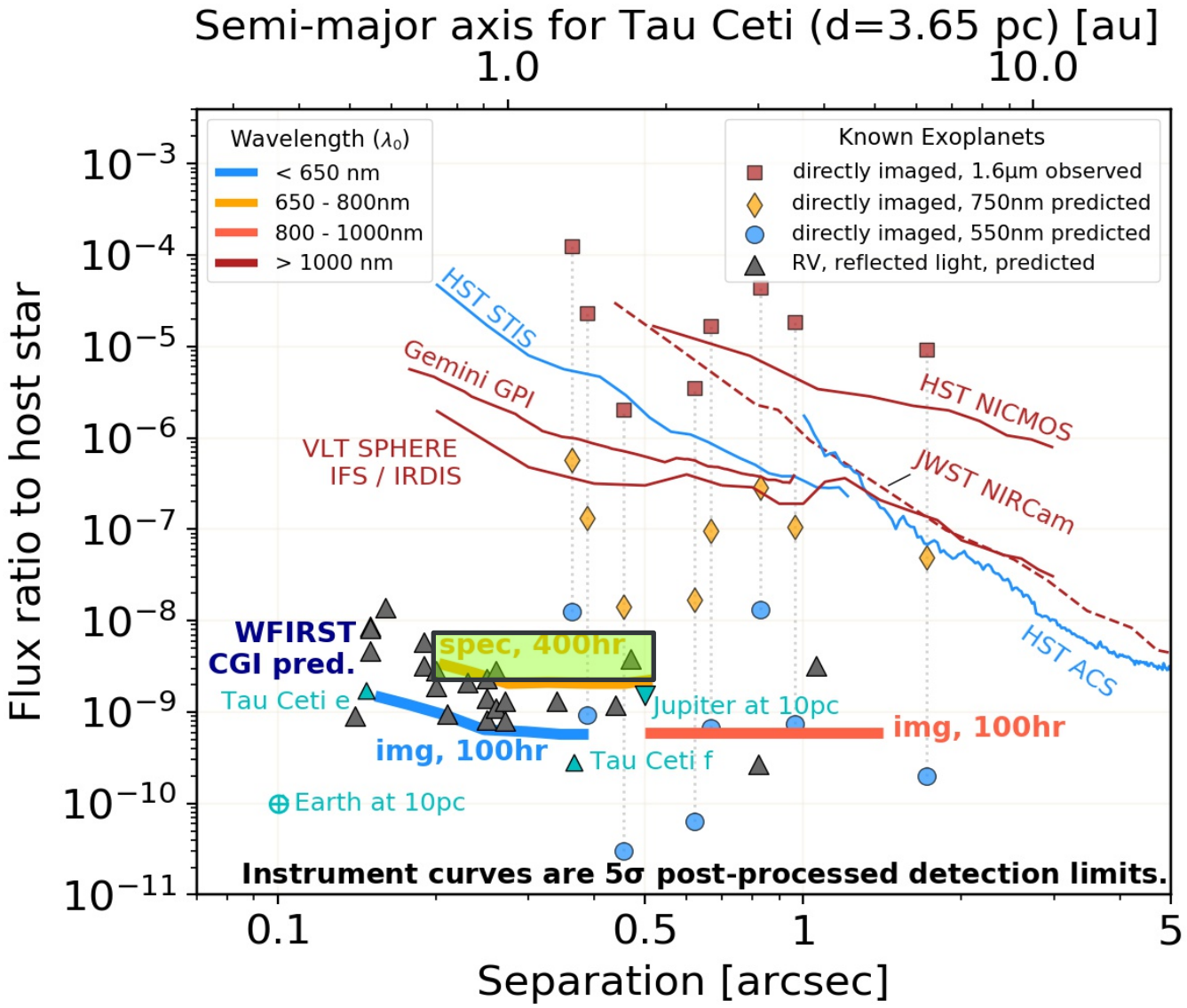
Spectra of young self-luminous planets: Beta Pic b, HR 8799 e, 51 Eri b



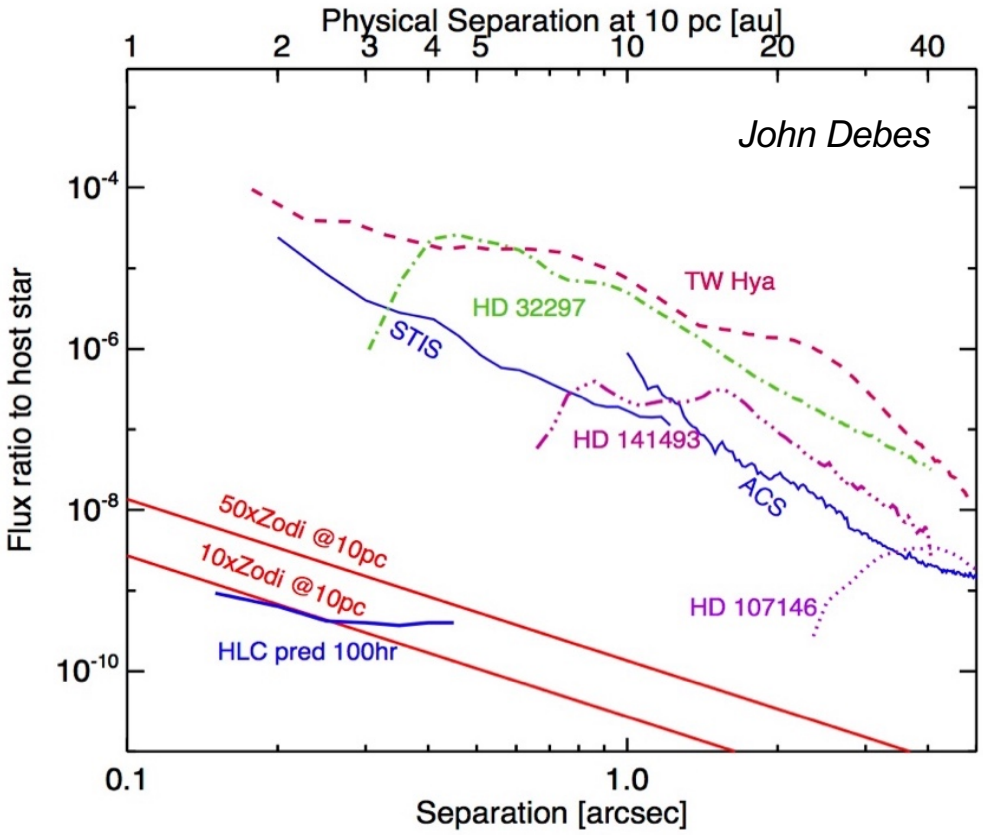


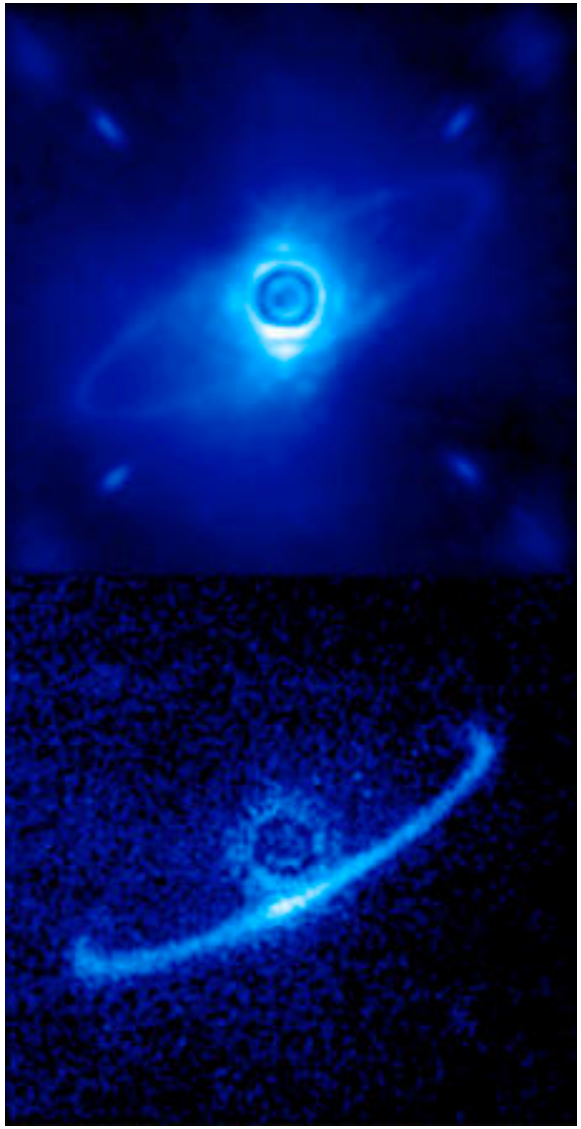
- CH4 abundance
- Cloud properties
- Halpha accretion?

Reflected light spectroscopy of mature RV planets

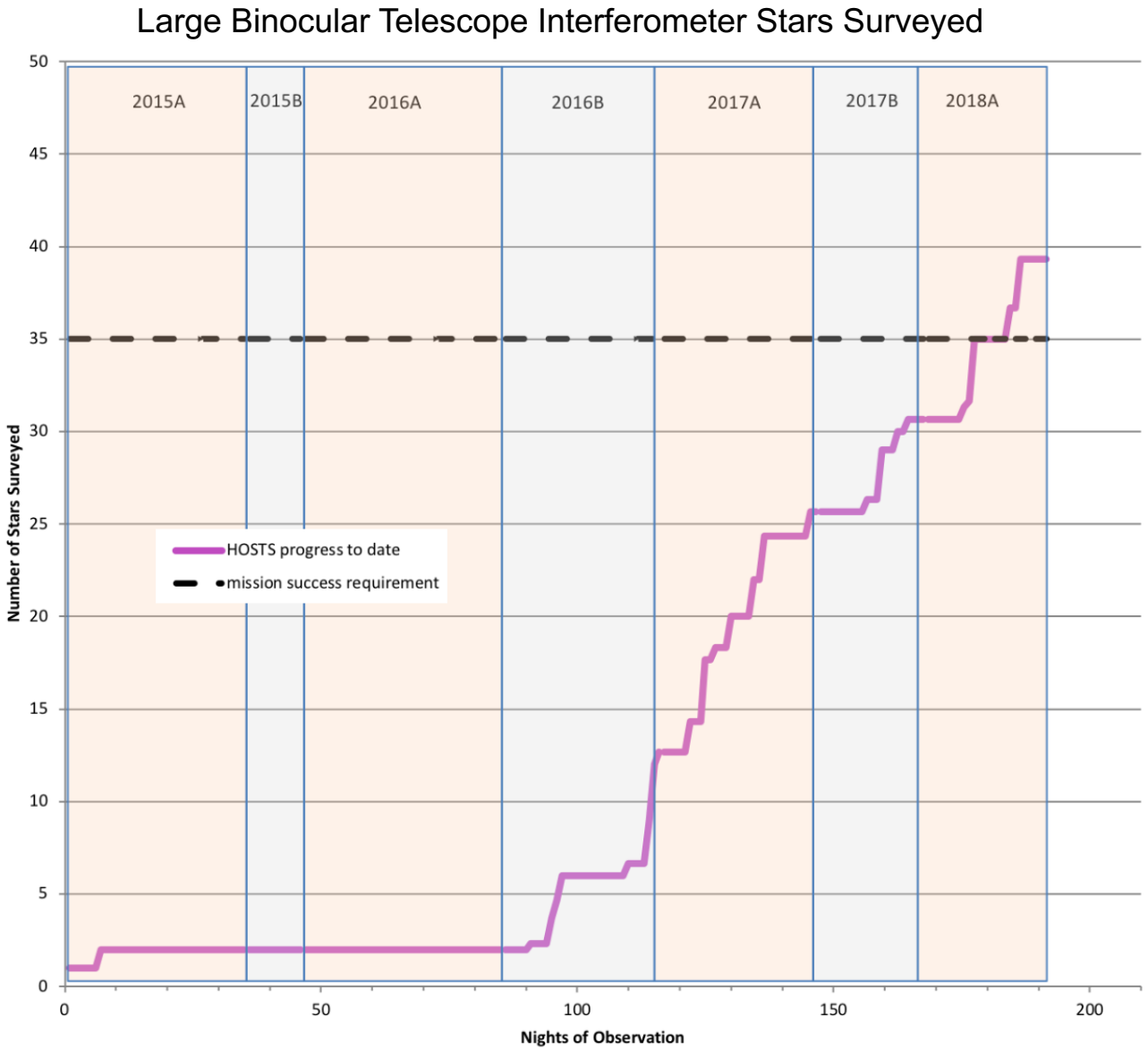


Imaging and Polarimetry of Debris Disks

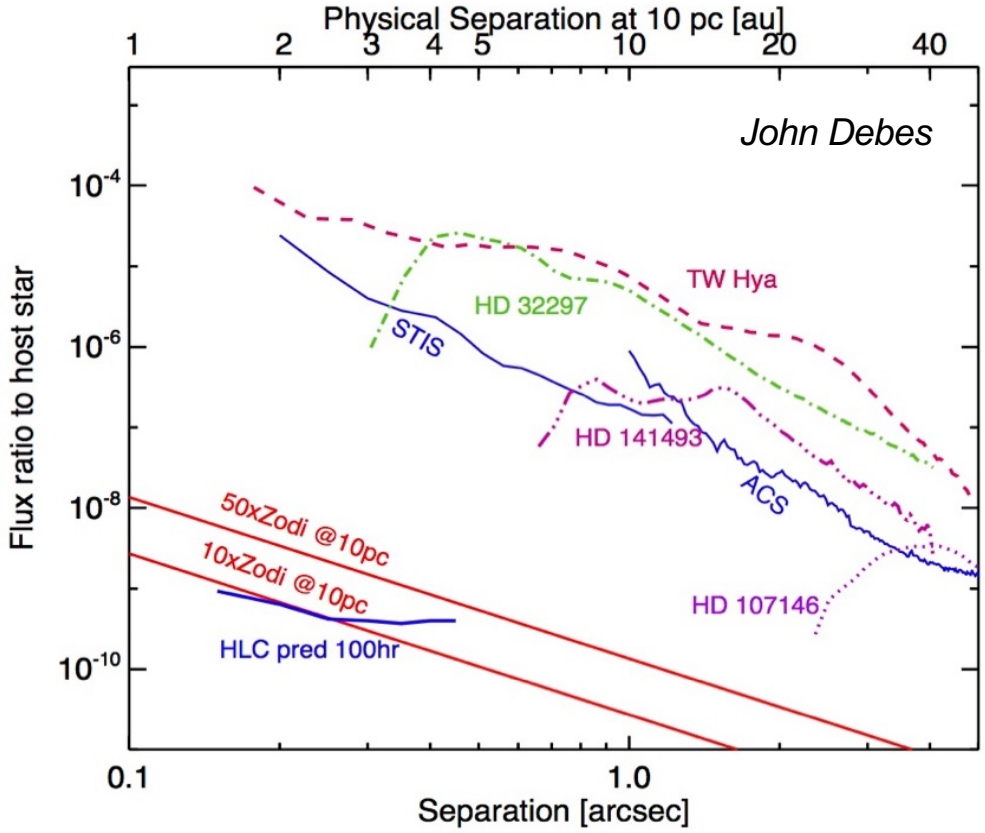




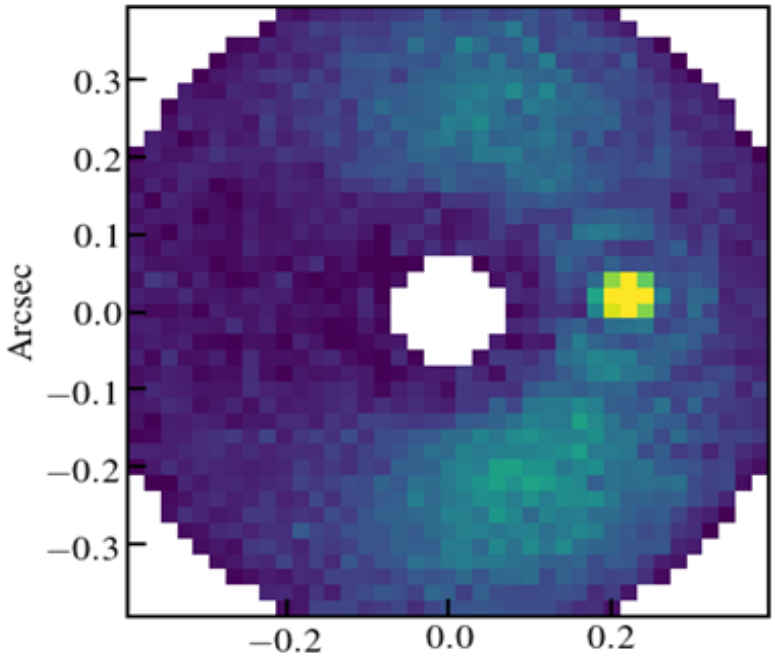
LBTI : most stars are not very dusty



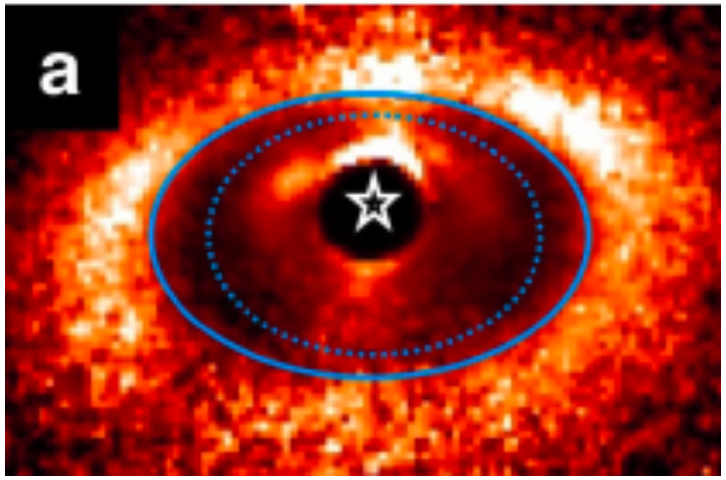
Exozodi : contaminants & targets



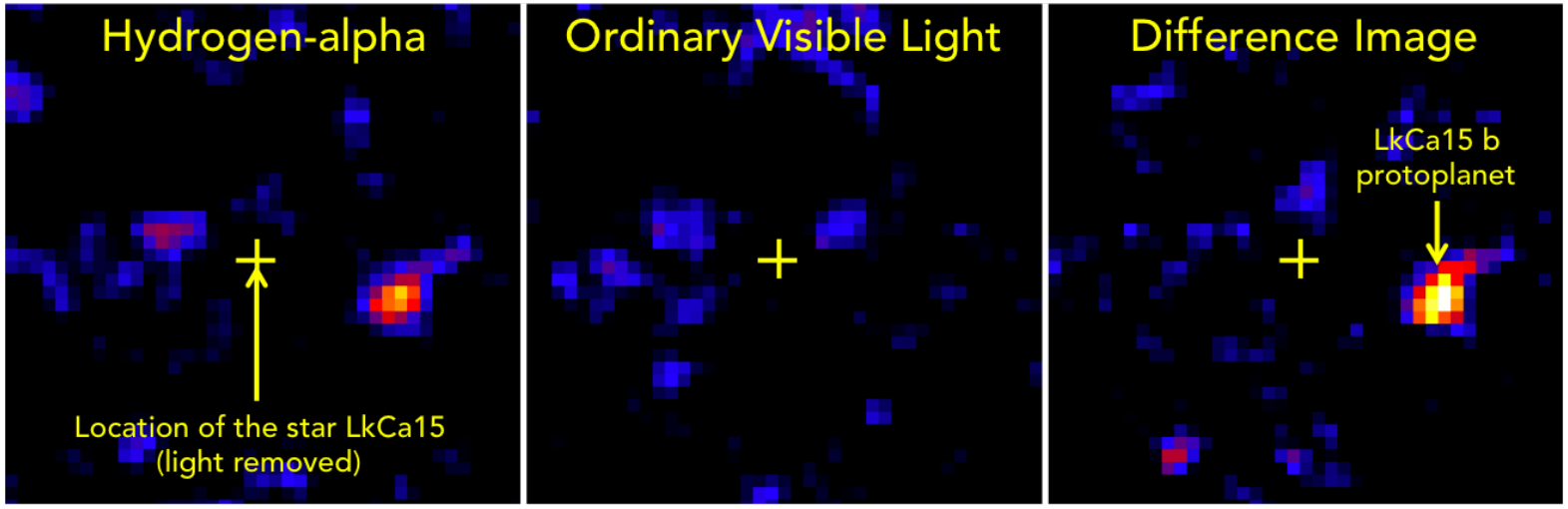
M. Rizzo, N. Zimmerman and the "Haystacks" team.
10zodi disk & embedded jovian planet located at 1.6 AU



Maybe in PSP: Protoplanetary disks & protoplanets

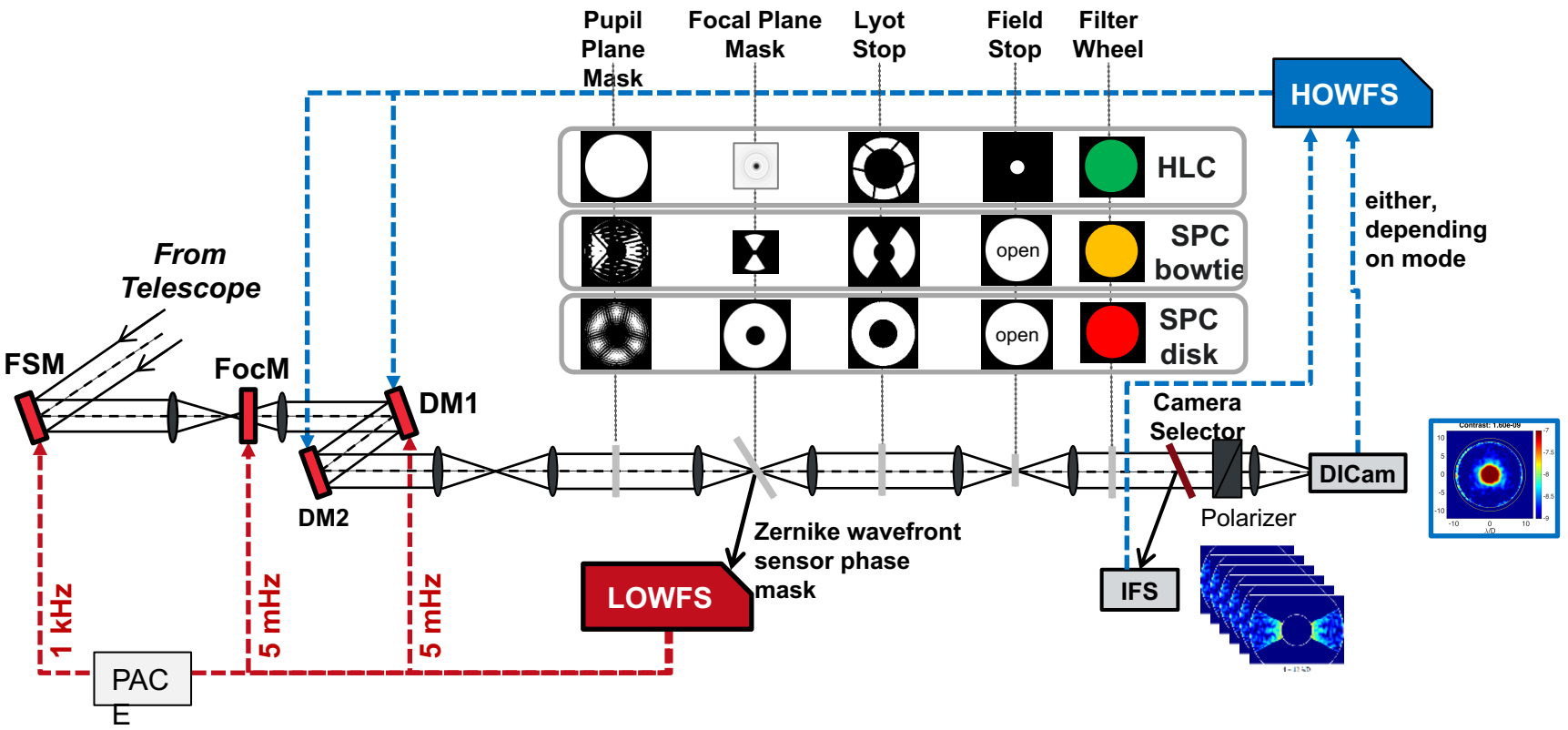


Thalmann et al. (2016)



Sallum et al. 2015

CGI Architecture

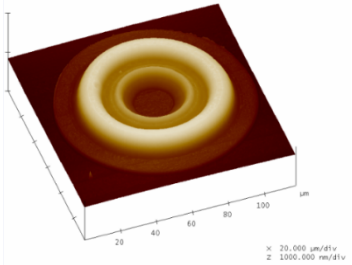


- Two selectable coronagraph technologies (HLC, SPC)
- Two deformable mirrors (DMs) for high-order wavefront control
- Low-order wavefront sensing & control (LOWFS&C)
- Direct imaging camera (DICam)
- Integral field spectrograph (IFS, R = 50)
- Photon-counting EMCCD detectors

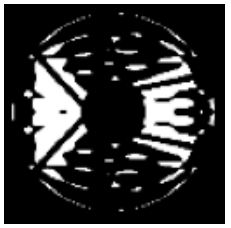
Successful Technology Maturation for CGI

- Pupil plane and focal plane masks for starlight suppression
  - Hybrid Lyot Coronagraph (HLC)
  - Shaped Pupil Coronagraph (SPC)
- Photon-counting electron-multiplying (EM) CCD for detection of very faint planets
  - Teledyne e2v
  - 1K×1K pixels
  - Radiation characterization
- Deformable mirrors for telescope surface error and drift correction
  - Northrop Grumman Xinetics
  - 48×48 actuators
  - Electrostrictive PMN (lead magnesium niobate)
  - Still requires environmental test of interconnect
- Coronagraph system-level performance demonstrated using a testbed with flight-like observatory disturbances:
  - Optical telescope simulator, with simulated pointing and thermal drift errors
  - High-order wavefront sensing and control to system to measure/correct telescope errors
  - Low-order wavefront sensing and control system to measure/correct telescope drift and provide tip/tilt error signal

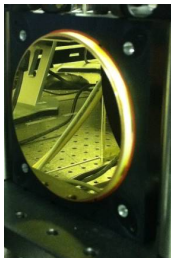
HLC mask image with an atomic force microscope

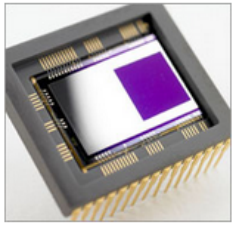


SPC mask image with an atomic force microscope

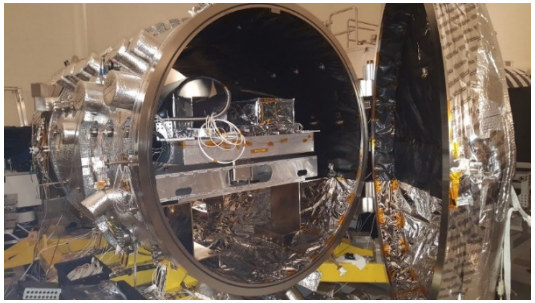


Xinetics 48 x 48 DM used in JPL's HCIT





E2V EMCCD used in photon-counting mode



Testbed
JPL's High Contrast Testbed

CGI Coronagraphs

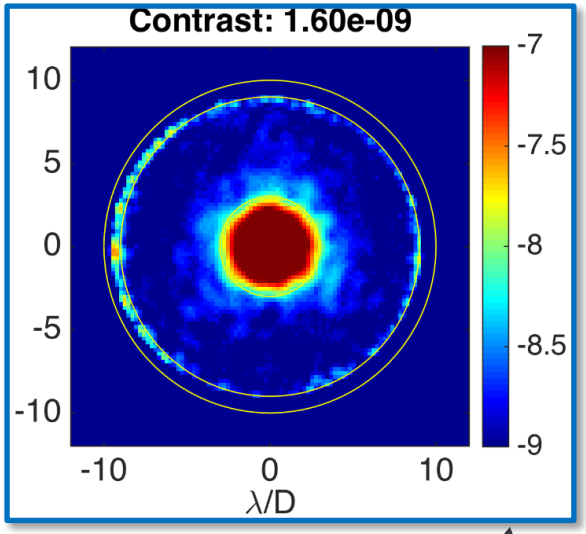
CGI Filter	λ_{center} (nm)	BW	Mask Type	Working Angle	Starlight Suppression Region
1	575	10%	HLC	3-9 λ/D	360°
2	660	18%	SPC bowtie	3-9 λ/D	130°
3	760	18%	SPC bowtie	3-9 λ/D	130°
4	825	10%	SPC wide FOV	6.5-20 λ/D	360°
4	825	10%	HLC	3-9 λ/D	360°

These five coronagraph masks will be installed in CGI. However, only the three CGI configurations supporting the “official observing modes” will be fully tested for the tech demo phase.

Imaging with Narrow Field of View Mode

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

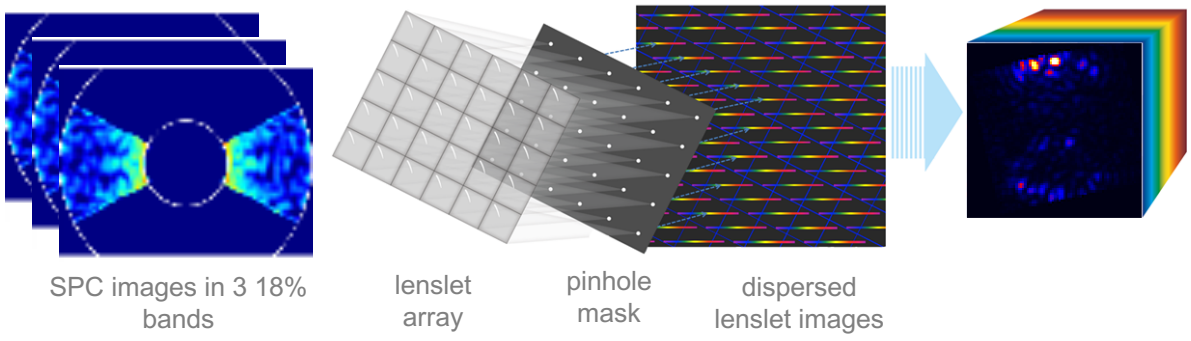
Dark hole for planet photometry and discovery centered at 575 nm with annular FOV from 3-9 λ/D



Spectroscopy Mode with Integral Field Spectrograph (IFS)

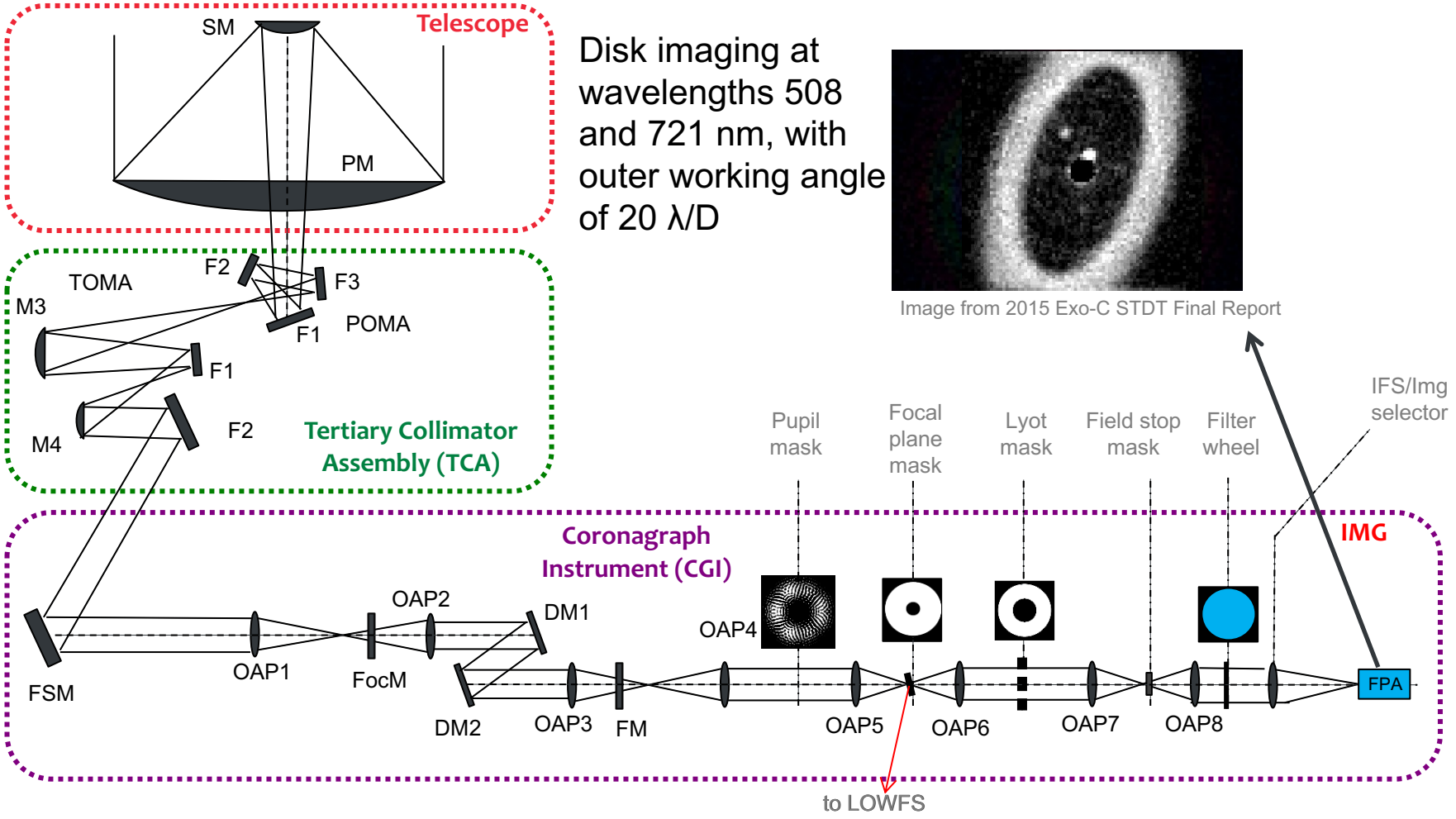
WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

The IFS uses 3 18% bands to produce R=50 spectra from 600 to 830 nm



Imaging with Wide Field of View Mode

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

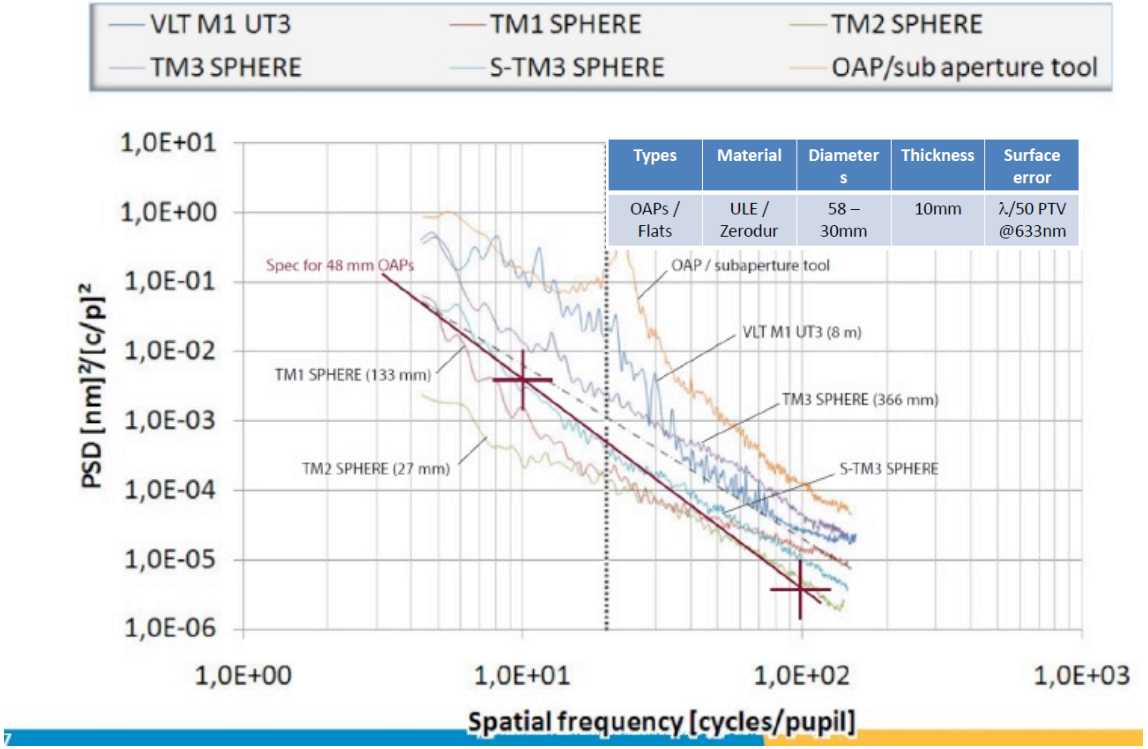


Disk imaging at wavelengths 508 and 721 nm, with outer working angle of 20 λ/D

Image from 2015 Exo-C STDT Final Report

Optics following the Deformable Mirror are Critical

- High precision off-axis parabolas to be provided by LAM using stress polishing techniques
- Critical since post deformable mirror; need to maintain wavefront error accuracy



Summary

- CGI will be the first “active” coronagraph in space
  - technology demonstration for HabEx/LUVIOR

- Capable of interesting science
  - Imaging & spectroscopy of young & mature planets and disks
  - Probable targets for tech demo
    - images of several reflected light Jupiters and circumstellar disks
    - Spectrum of 1 reflected light Jupiter and 1 self-luminous giant planet
    - Polarimetry of 1 debris disk
    - *May* image 1-2 exozodi
    - *May* image 1 protoplanetary disk

- Notional observing program
  - 3 months of tech demo observing in first 1.5 years of WFIRST mission
  - If meet success criteria, 1 year Participating Science Program
    - Calls for PSPs expected early 2020s
    - Shared w/ WFI
  - If successful, follow-on 2.5 year science program
    - Shared w/ WFI


NASA

Observation: Integration and Chop Cycle